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(71) Applicant(s)

The University Court of the University of Glasgow
(Incorporated in the United Kingdom)
University Avenue, Glasgow, G12 8QQ,
United Kingdom

(72) Inventor(s)

Paulo Vicente da Silva Marques
James Ronald Bonar
James Stewart Aitchison

(74) Agent and/or Address for Service

Murgitroyd & Company
373 Scotland Street, GLASGOW, G5 8QA,
United Kingdom

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(56) Documents Cited

EP 0803589 A EP 0617301 A EP 0607884 A
US 4871221 A

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UK CL (Edition Q) G2J JGDA
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(54) Abstract Title

Waveguides

(57) A waveguide for an optical circuit comprises a substrate 6; a buffer layer 7 formed on the substrate; a doped lower cladding layer 8 formed on the buffer layer; a doped waveguide core 13 formed on the lower cladding layer; and a doped upper cladding layer 12 embedding the waveguide core. The waveguide core includes mobile dopant ions, such which as P or F have diffused into the upper cladding layer and the lower cladding layer to form an ion diffusion region around said waveguide core such that the waveguide core boundary walls are substantially smooth. Methods of fabricating the waveguide are also described. Cladding layers 8 and 13 are preferably doped with P or B ions.

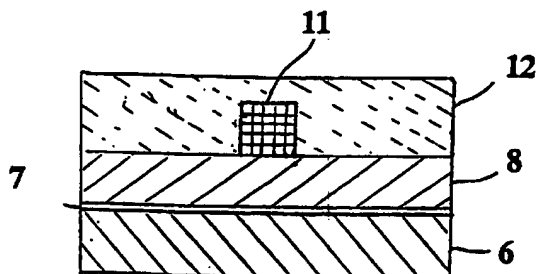


FIG. 2C

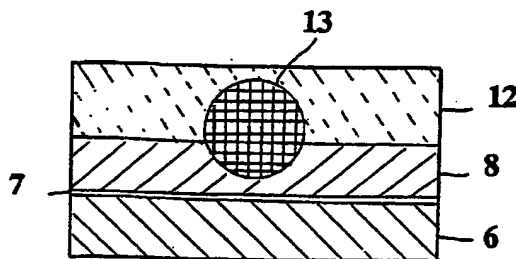


FIG. 2E

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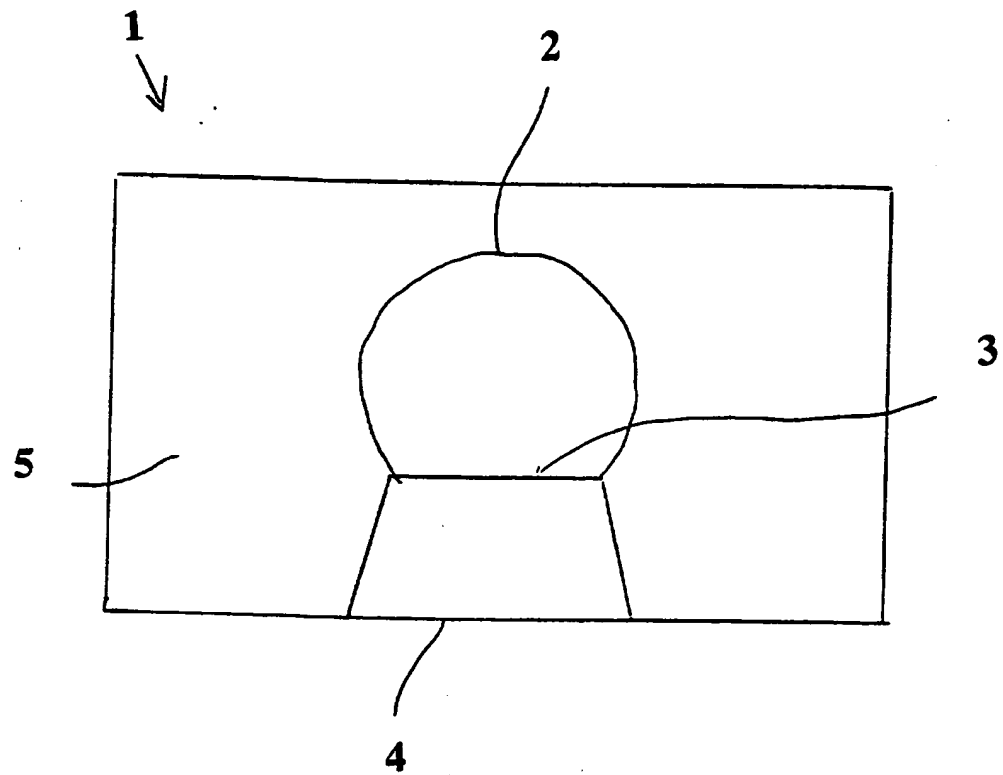


FIG. 1

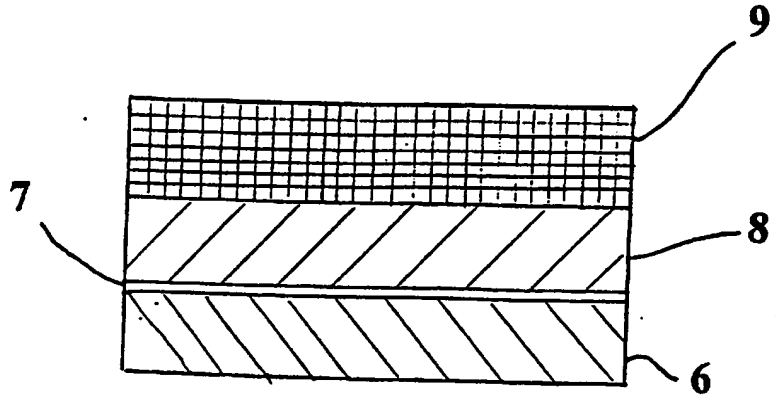


FIG. 2A

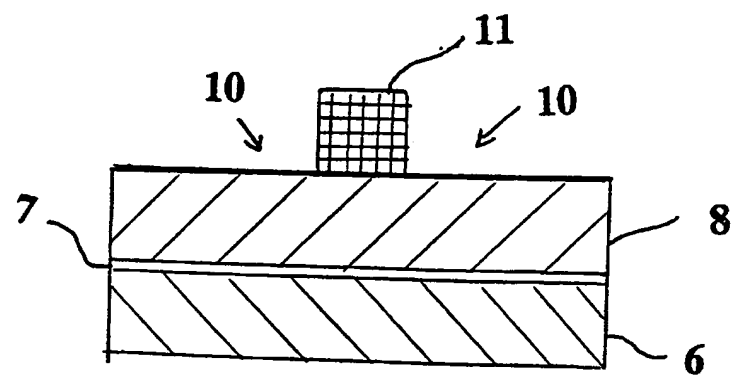


FIG. 2B

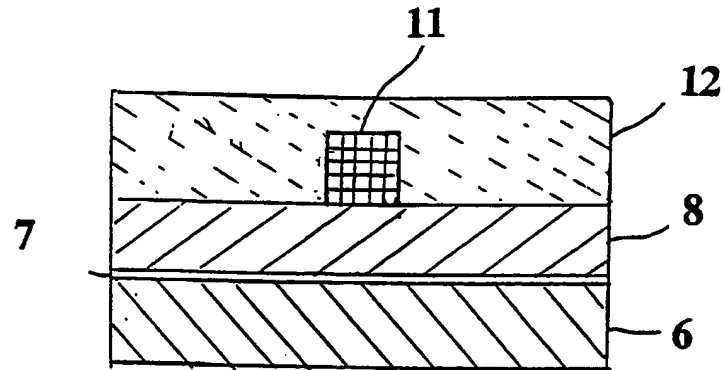


FIG. 2C

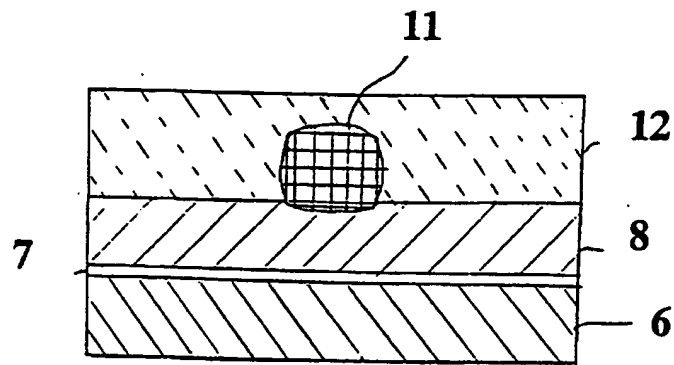


FIG. 2D

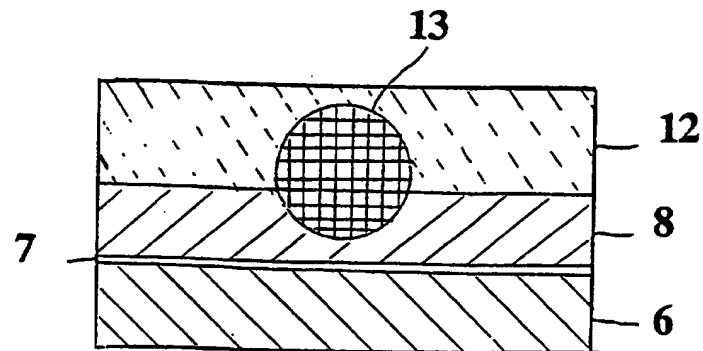


FIG. 2E

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10 **WAVEGUIDE FOR AN OPTICAL CIRCUIT AND METHOD OF**
11 **FABRICATION THEREOF**

12

13 FIELD OF THE INVENTION

14

15 The present invention relates to a waveguide for an
16 optical circuit, and a method of fabrication thereof.

17

18 The method relates in particular to the fabrication of
19 a waveguide for an optical circuit with smoothed
20 waveguide core boundaries. More specifically, the
21 method relates to the fabrication of a rounded,
22 elliptical or circular waveguide core by the isotropic
23 diffusion of dopants in a core layer of a
24 phosphosilicate waveguide wafer, such that the diffused
25 core layer forms the circular waveguide core. This
26 diffusion is thermally promoted either during the
27 deposition of an upper cladding layer or by subsequent
28 thermal processing of the waveguide wafer.

29

30 BACKGROUND OF THE INVENTION

31

32 The general process of fabricating a glass waveguide
33 for optical circuits comprises forming at least one
34 buffer layer, e.g. a thermal oxide layer, on a silicon
35 wafer substrate. Additional buffer layers and/or at

1 least one lower cladding layers may then be formed on
2 top of the buffer layer. A core layer composed of a
3 doped silica film is then formed on top of the buffer
4 layer or lower cladding layer.

5
6 The core layer is then etched, for example, by reactive
7 ion techniques, to form a square or rectangular
8 waveguide or other suitable cross-sectional profile.
9 The etched core is then embedded by an upper cladding
10 layer.

11 The core layer refractive index is usually higher than
12 that of the surrounding layers. This concentrates the
13 propagation of light in the core layer.

14
15 Planar channel waveguides are usually formed using dry
16 etch methods to produce waveguides with square or
17 rectangular cross-sections. Such angular waveguides
18 have several disadvantages, in particular the
19 geometrical mismatch between the waveguides and optical
20 fibres in an optical circuit. The production of channel
21 waveguides with a circular cross-section is
22 particularly advantageous in that this increases the
23 transmission efficiency between the waveguide and the
24 rest of an optical circuit.

25
26 Channel waveguides are also susceptible to scatter loss
27 (Mie scattering) due to imperfections in their
28 sidewalls. This is reduced by smoothing the profile of
29 the waveguide and this provides low propagation loss in
30 the waveguides.

31
32 Circular optical waveguides are known in principle (for
33 example, see Sun et al., "Silica-based circular cross-
34 sectioned channel waveguides", IEEE Photonics
35 Technology Letters, 3, p.p. 238-240, 1991). Sun et
36 al., disclose large dimension ($\sim 50\mu\text{m}$) GeO_2 doped silica

1 waveguides which are reactive ion etched to form
2 rectangular channel cross-sections. This method
3 involves depositing a lower cladding layer with a
4 reduced amount of Germanium doped silicon on to the
5 wafer substrate prior to the deposition of a core
6 layer. When the wafer is placed in the selective wet
7 etch, the lower cladding layer is etched at a much
8 faster rate to form a pedestal underneath the core
9 region.

10

11 According to Sun et al., the waveguide can then be
12 heated above the core softening temperature so that the
13 surface tension of the glass functions to round the
14 waveguide core. Such wet etching techniques are time
15 consuming and moreover, do not offer truly circular
16 cross sections as the core cannot be rounded at the
17 interface between the core layer and the pedestal
18 (i.e., the lower cladding layer lying directly beneath
19 the core).

20

21 The current invention in contrast relies on the
22 mobility of dopant ions in a square or rectangular
23 etched core to migrate outwards into both upper and
24 lower cladding layers. This forms waveguides which
25 have substantially smoothed boundary walls, in
26 particular the side walls are smoothed.

27

28 Further diffusion rounds the core region, and providing
29 the diffusion is sufficiently isotropic the core region
30 becomes sufficiently rounded to form a circular
31 waveguide. This diffusion is thermally promoted either
32 during the consolidation of the upper cladding layer or
33 during subsequent thermal processing. By selecting the
34 composition of the upper and lower cladding layers, the
35 refractive indexes and consolidation temperatures can
36 be chosen to modify the rate at which the core dopant

1 ions diffuse into each layer and the ellipticity of the
2 resulting waveguide core accordingly adjusted.

3

4

5 SUMMARY OF THE INVENTION

6

7 According to a first aspect of the present invention,
8 there is provided a waveguide for an optical circuit
9 comprising:

10 a substrate;

11 a doped lower cladding layer;

12 a doped waveguide core formed on the lower
13 cladding layer; and

14 a doped upper cladding layer embedding the
15 waveguide core;

16 wherein the waveguide core includes mobile dopant
17 ions which have diffused into the upper cladding layer
18 and the lower cladding layer to form an ion diffusion
19 region around said waveguide core such that the
20 waveguide core boundary walls are substantially smooth.

21

22 According to a second aspect of the present invention,
23 there is provided a method for fabricating a waveguide
24 comprising the steps of:

25 providing a substrate;

26 forming a doped lower cladding layer;

27 forming a doped core layer on the lower cladding
28 layer;

29 forming a waveguide core from the core layer;

30 forming a doped upper cladding layer to embed the
31 waveguide core;

32 wherein mobile ion dopants included in the core
33 layer undergo diffusion into the surrounding upper
34 cladding layer and lower cladding layer to form an ion
35 diffusion region around the waveguide core such that
36 the waveguide core boundary walls are substantially

1 smooth.

2

3 DESCRIPTION OF THE DRAWINGS

4

5 Embodiments of the present invention will now be
6 described by way of example only with reference to the
7 accompanying drawings in which:-

8

9 Fig. 1 is a cross-sectional diagram of a conventionally
10 rounded waveguide;

11

12 Figs. 2A to 2E are a cross-sectional diagrams showing
13 stages in the fabrication of a rounded waveguide
14 according to the present invention;

15

16 DETAILED DESCRIPTION OF THE INVENTION

17

18 With reference to the drawings, there is described now
19 a waveguide for an optical circuit and a method of
20 fabrication thereof according to the present invention.

21

22 A waveguide produced by conventional techniques which
23 can partially round the cross-section of the core layer
24 of a waveguide is shown in Fig.1. This illustrates such
25 a waveguide 1 with a rounded core upper cross-section 2
26 and flat base 3 supported by a pedestal 4 embedded in a
27 cladding layer 5 as might be formed by the conventional
28 method of *Sun et al.*

29

30 The present invention provides a waveguide which does
31 not exhibit the flat base 3 shown in Fig.1. Various
32 stages in the method of fabricating such a waveguide
33 will now be described with reference to Figs. 2A to 2E.

34

35 Fig. 2A is a schematic diagram showing the preliminary
36 stages in a method of fabricating a waveguide with an

1 elliptical or rounded cross-section from a silicon
2 wafer according to a first embodiment of the invention.

3
4 In this embodiment, a silicon substrate 6 is covered
5 with a buffer layer 7 comprising thermally oxidised
6 silicon. In alternative embodiments of the invention,
7 the substrate 6 comprises silica and sapphire and the
8 buffer layer 7 further includes at least one Phosphorus
9 oxide and/or Boron oxide. The thickness of the
10 thermally oxidised silicon buffer layer 7 ranges
11 between 0.2 μm and 20 μm .

12
13 A lower cladding layer 8, doped with Phosphorus and
14 Boron ions and having a refractive index matched to the
15 buffer layer 7, is then deposited using a Flame
16 Hydrolysis Deposition (FHD) process on to the buffer
17 layer 7, and is consolidated either in an electrical
18 furnace or by using an FHD burner.

19
20 By way of example, the FHD process used for deposition
21 of the lower cladding layer 8 can employ the following
22 input feed flow rates for the feed gases:-
23 Shroud gas 5 litres/min; O_2 4 litres/min;
24 H_2 2 litres/min; SiCl_4 carrier gas 0.15 litres/min;
25 PCl_3 carrier gas 0.04 litres/min;
26 BCl_3 carrier gas 0.09 litres/min. The halides are
27 carried, for example, by an N_2 carrier gas, and the
28 shroud gas can, for example, be N_2 .

29
30 The lower cladding layer 8 formed comprises silica,
31 Phosphorus oxide, and Boron oxide; for example $\text{SiO}_2\text{-P}_2\text{O}_5\text{-}$
32 B_2O_3 . In alternative embodiments, the lower cladding
33 layer 8 may contain dopant ions in addition to $\text{SiO}_2\text{-P}_2\text{O}_5\text{-}$
34 B_2O_3 . The doping levels for the silica, Phosphorus oxide
35 and Boron oxide in the lower cladding layer 8 are 82
36 wt% silica, 5 wt% Phosphorus oxide and 13 wt% Boron

1 oxide. Varying the flow rates of the input gases in
2 the FHD burner results in different doping levels. In
3 other embodiments of the invention, the preferred
4 doping levels range between 75 to 95 wt% silica, 1 to 7
5 wt% Phosphorus oxide and 4 to 18 wt% Boron oxide, or
6 alternatively range between 80 to 90 wt% silica, 2.5 to
7 6 wt% Phosphorus oxide, and 7.5 to 14 wt% Boron oxide.
8

9 The lower cladding layer 8 is consolidated by fully
10 fusing the layer in an electric furnace at a
11 temperature of 1250°C, which is in a preferred range of
12 temperatures of between 1100°C to 1350°C.
13

14 In alternative embodiments, the lower cladding layer 8
15 is deposited using an FHD process and can be
16 consolidated at different temperatures within a range
17 of temperatures of between 950°C to 1400°C.
18

19 In a further alternative, the lower cladding layer 8 is
20 deposited by a Flame Hydrolysis Deposition (FHD)
21 process and partially consolidated at this stage and
22 fully consolidated subsequently.
23

24 The thickness of the lower cladding layer 8 deposited
25 is 2 μm but can range between 1 μm and 20 μm .
26

27 In alternative embodiments, where no buffer layer is
28 employed, the lower cladding layer 8 can be formed
29 directly on top of the substrate 6.
30

31 A core layer 9 comprising Phosphorus oxide and silica,
32 for example, $\text{P}_2\text{O}_5\text{-SiO}_2$, is then formed on the lower
33 cladding layer 8. The refractive index of the core
34 layer 9 differs from that of the lower cladding layer 8
35 by 0.75%, and may differ by a value within the range of
36 0.05 % to 2 %.

1 By way of example, the FHD process used for deposition
2 of the core layer 9 can employ the following input feed
3 flow rates for the feed gases:-
4 Shroud gas 5 litres/min; O₂ 6 litres/min;
5 H₂ 4 litres/min; SiCl₄ carrier gas 0.15 litres/min;
6 PCl₃ carrier gas 0.018 litres/min. The halides are
7 carried, for example, by an N₂ carrier gas, and the
8 shroud gas can, for example, be N₂.

9
10 The core layer 9 is consolidated by fully fusing the
11 layer in an electric furnace at a temperature of
12 1200°C, which is in a preferred range of temperatures
13 of between 1100°C to 1385°C.

14
15 In alternative embodiments, the core layer 9 is
16 deposited using an FHD process and can be consolidated
17 at different temperatures within a range of
18 temperatures of between 950°C to 1400°C.

19
20 In a further alternative, the core layer 9 is partially
21 consolidated at this stage and consolidated
22 subsequently.

23
24 The dopant levels for the core layer 9 are 80 wt%
25 silica and 20 wt% Phosphorus oxide in the preferred
26 embodiment. In alternative embodiments, the input
27 gases into the FHD burner are varied to give core
28 dopant levels between 75 to 95 wt% silica and 5 to 25
29 wt% Phosphorus oxide respectively. The thickness of
30 the core layer deposited is 6 µm but can range between
31 2 µm and 60 µm.

32
33 The core layer mobile ion dopants include Phosphorus
34 ions but could, for example, include Fluorine ions. In
35 alternative embodiments, the core layer 9 is doped
36 Phosphorus and co-doped with ions with desired

1 properties to effect reduction of the sintering
2 temperature and/or to effect increase of the core layer
3 refractive index. The co-dopants may be selected from
4 the group comprising Aluminium, Boron, Germanium, Tin
5 and/or Titanium. For example, co-doping with Germanium
6 reduces the sintering temperature and raises the silica
7 based core layer 9 refractive index so that the
8 refractive index is higher than the refractive index of
9 the lower cladding layer 8 on top of which the core
10 layer 9 is deposited.

11

12 The lower cladding layer 8 is susceptible to
13 interdiffusion from the dopant ions from the core layer
14 9. In contrast, the buffer layer 7 acts as a barrier
15 against interdiffusion.

16

17 Fig. 2B shows the subsequent stage in the method of
18 fabricating an optical waveguide in which the core
19 layer 9 is redefined by removing regions 10 by a
20 reactive ion etching (RIE) technique to form a square
21 waveguide core 11. In general, a square or rectangular
22 waveguide core 11 whose dimensions range from 2 μm to
23 60 μm will be suitable in the method of fabricating an
24 optical waveguide, preferred dimensions being such as
25 to give a waveguide core 11 of 6 μm x 6 μm .

26

27 Alternative techniques for forming a square or
28 rectangular waveguide core 11 can be used, or a
29 combination of techniques. For example, dry etching
30 techniques (e.g. reactive ion etching, ion milling,
31 and/or plasma etching processes), a photolithographic
32 technique, and/or a mechanical sawing process may be
33 used.

34

35 Subsequently, the waveguide core 11 is embedded by an
36 upper cladding layer 12 (as shown in Fig. 2C)

1 comprising Phosphorus oxide, Boron oxide and silica.
2 Preferably, the upper cladding layer 12 has the same
3 composition as the lower cladding layer 8 (P_2O_5 - B_2O_3 -
4 SiO_2) and the same refractive index. Alternatively, the
5 upper cladding layer 12 can have a different
6 composition from the lower cladding layer 8 but can
7 have substantially the same refractive index. The
8 upper cladding layer 12 can be deposited using the same
9 input gas flow parameters into the FHD apparatus as for
10 the lower cladding layer 8.

11
12 The upper cladding layer 12 is then consolidated in a
13 furnace and by adjusting the duration and temperature
14 of the heat treatment the amount of diffusion of the
15 dopant ions in the waveguide core 11 can be adjusted.

16
17 The upper cladding layer 12 is consolidated by fully
18 fusing the upper cladding layer 12 in an electric
19 furnace for about 90 minutes at a minimum temperature
20 of 1050°C and preferably at a temperature of 1200°C,
21 which is in a preferred range of temperatures of
22 between 1100°C to 1250°C.

23
24 The consolidation temperature of the upper cladding
25 layer 12 is a minimum of 1050 °C for the given co-
26 dopant levels. In alternative embodiments, for other
27 co-dopant levels, the upper cladding layer 12 is
28 deposited using an FHD process and can be consolidated
29 at different temperatures within a range of
30 temperatures of between 950°C to 1250°C. By suitably
31 varying the co-dopant levels in the upper cladding
32 layer 12 the consolidation temperature can be reduced
33 to below 950°C.

34
35 Fig. 2D shows how the consolidation temperature of the
36 upper cladding layer 12 promotes diffusion of the

1 mobile core dopant ions into the upper cladding layer
2 12 and lower cladding layer 8. The composition of the
3 upper and lower cladding layers 8 and 12 gives a
4 diffusion length of $2\mu\text{m}$ when the consolidation
5 temperature of the core layer 9 and upper cladding
6 layer 12 is 1200°C . More typically, the diffusion
7 length is between the range of $0.1\mu\text{m}$ to $3\mu\text{m}$ for the
8 preferred ranges of consolidation temperatures.
9

10 The upper cladding layer 12 is consolidated at a
11 temperature which is the same as or greater than a
12 temperature which promotes efficient diffusion of the
13 waveguide core 11.
14

15 The ion dopant concentration in the lower cladding
16 layer 8 and upper cladding layer 12 is chosen so that
17 the waveguide core 11 has a higher concentration of
18 dopant ions to promote diffusion of the waveguide core
19 11 dopant ions into the lower cladding layer 8 and
20 upper cladding layer 12. In the preferred embodiment,
21 the diffusion of the mobile ion dopants in the
22 waveguide core 11 into the surrounding cladding layers
23 8 and 12 occurs during consolidation of the upper
24 cladding layer 12, during which the core boundaries of
25 the waveguide core 11 are rounded and a waveguide 13 is
26 formed which is circular in cross-section.
27

28 In an alternative embodiment, subsequent thermal
29 processing after the consolidation of the upper
30 cladding layer 12 promotes diffusion of the mobile ion
31 dopants in the waveguide core 11 into the surrounding
32 cladding layers 8 and 12.
33

34 Fig. 2E shows the resulting rounded waveguide 13.
35

36 In other embodiments of the invention, a silica based

1 waveguide core 11 may be doped with Phosphorus and
2 Germanium to raise the refractive index of the
3 waveguide core 11 and to reduce the consolidation
4 temperature of the waveguide core 11. Alternative
5 techniques may be used to redefine the waveguide core
6 11 from the core layer 9; e.g. photolithographic,
7 plasma etching processes, ion milling process,
8 mechanical sawing process, and RIE processes.

9
10 In other embodiments, the waveguide core 11 may
11 comprise more than one core layer 9. Such core layers
12 9 could be chosen to have substantially the same
13 refractive index but differ in material composition.

14
15 Other embodiments of the invention may require
16 additional interdiffusion upper cladding layers 12 and
17 lower cladding layers 8 to be deposited above and/or
18 below the waveguide core 11. To promote isotropic
19 diffusion, the lower cladding layers 8 may have the
20 same composition and/or the same refractive index as
21 that of the upper cladding layers 12. The isotropy of
22 the refractive index surrounding the waveguide core 11
23 promotes circular diffusion and a circular waveguide
24 core 13 results.

25
26 In other embodiments, a Chemical Vapour Deposition
27 (CVD) method, or a Plasma Enhanced Chemical Vapour
28 Deposition (PECVD) method, or a combination of these
29 methods can be used to form the cladding layers 8 and
30 12 and the core layer 9. Subsequent thermal processing
31 of the waveguide promotes diffusion of ion dopants from
32 the waveguide core 11 into the surrounding upper
33 cladding and lower cladding layers 8 and 12.

34
35 In other embodiments, the lower cladding layer 8 may be
36 only partially consolidated before the core layer 9 is

1 deposited thereon and fully consolidated when the core
2 layer 9 is consolidated. Furthermore, the waveguide
3 core 11 may only be partially consolidated when the
4 upper cladding layer 12 is formed thereon and may be
5 fully consolidated when the upper cladding layer 12 is
6 consolidated. Also, the FHD burner can be used for
7 fusing by passing the burner over the waveguide to fuse
8 the lower cladding and upper cladding layers 8 and 12
9 and to fuse the core layer 9.

10

11 While several embodiments of the present invention have
12 been described and illustrated, it will be apparent to
13 those skilled in the art once given this disclosure
14 that various modifications, changes, improvements and
15 variations may be made without departing from the
16 spirit or scope of this invention.

1 Claims:

2

3 1 A waveguide for an optical circuit comprising:

4 a substrate;

5 a doped lower cladding layer;

6 a doped waveguide core formed on the lower

7 cladding layer; and

8 a doped upper cladding layer embedding the

9 waveguide core;

10 wherein the waveguide core includes mobile dopant

11 ions which have diffused into the upper cladding layer

12 and the lower cladding layer to form an ion diffusion

13 region around said waveguide core such that the

14 waveguide core boundary walls are substantially smooth.

15

16 2. A waveguide as claimed in Claim 1, and further

17 including a buffer layer formed on the substrate and

18 wherein the lower cladding layer is formed on the

19 buffer layer.

20

21 3. A waveguide as claimed in either preceding claim,

22 wherein the substrate comprises silicon and/or silica

23 and/or sapphire.

24

25 4. A waveguide as claimed in Claim 3, wherein said

26 buffer layer includes a thermally oxidised layer of the

27 substrate.

28

29 5. A waveguide as claimed in any preceding claim,

30 wherein the buffer layer comprises doped silica.

31

32 6. A waveguide as claimed in any preceding claim,

33 wherein the thickness of the buffer layer is in the

34 range 0.2 μ m to 20 μ m.

35

36 7. A waveguide as claimed in any preceding claim,

1 wherein the lower cladding layer comprises doped
2 silica.

3

4 8. A waveguide as claimed in any preceding claim,
5 wherein the lower cladding layer includes at least one
6 Phosphorus oxide and/or at least one Boron oxide.

7

8 9. A waveguide as claimed in Claim 8, wherein the
9 lower cladding layer includes at least one Phosphorus
10 oxide and at least one Boron oxide and wherein the
11 Phosphorus oxide to Boron oxide ratio is such that the
12 lower cladding layer refractive index is substantially
13 equal to the refractive index of the buffer layer.

14

15 10. A waveguide as claimed in any preceding claim,
16 wherein the lower cladding layer includes doped silica,
17 at least one Phosphorus oxide and at least one Boron
18 oxide and wherein the silica:Phosphorus oxide:Boron
19 oxide ratio is in the range of 75 to 95 wt% silica:1 to
20 7 wt% Phosphorus oxide:4 to 18 wt% Boron oxide.

21

22 11. A waveguide as claimed in Claim 10, wherein the
23 lower cladding layer has a silica:Phosphorus
24 oxide:Boron oxide ratio in the range of 80 to 90 wt%
25 silica:2.5 to 6 wt% Phosphorus oxide:7.5 to 14 wt%
26 Boron oxide.

27

28 12. A waveguide as claimed in Claim 11, wherein the
29 lower cladding layer has a silica; to Phosphorus oxide;
30 to Boron oxide ratio of 82 wt% silica; to 5 wt%
31 Phosphorus oxide; to 13 wt% Boron oxide.

32

33 13. A waveguide as claimed in any preceding claim,
34 wherein the thickness of the lower cladding layer is
35 1 μ m to 20 μ m.

36

- 1 14. A waveguide as claimed in any preceding claim,
2 wherein the waveguide core comprises doped silica.
3
- 4 15. A waveguide as claimed in any preceding claim,
5 wherein said mobile dopant ions of the waveguide core
6 include Phosphorus and/or Fluorine and/or compounds of
7 these elements.
8
- 9 16. A waveguide as claimed in any preceding claim,
10 wherein dopant ions of the waveguide core include
11 Phosphorus and/or Fluorine and/or Aluminium and/or
12 Boron and/or Germanium and/or Tin and/or Titanium
13 and/or compounds of these elements.
14
- 15 17. A waveguide as claimed in any preceding claim,
16 wherein the waveguide core includes Phosphorus oxide
17 and/or Boron oxide.
18
- 19 18. A waveguide as claimed in Claim 17, wherein the
20 waveguide core comprises P_2O_5 - SiO_2 .
21
- 22 19. A waveguide as claimed in any preceding claim,
23 wherein the refractive index of the waveguide core
24 differs from that of the lower cladding layer by at
25 least 0.05%.
26
- 27 20. A waveguide as claimed in any preceding claim,
28 wherein the waveguide core includes silica, and at
29 least one Phosphorus oxide and wherein the silica to
30 Phosphorus oxide ratio is in the range of 75 to 95 wt%
31 silica to 5 to 25 wt% Phosphorus oxide.
32
- 33 21. A waveguide as claimed in Claim 20, wherein the
34 waveguide core has a silica to Phosphorus oxide ratio
35 of 80 wt% silica to 20 wt% Phosphorus oxide.
36

1 22. A waveguide as claimed in any preceding claim,
2 wherein the thickness of the waveguide core is in the
3 range $2\mu\text{m}$ to $60\mu\text{m}$.

4
5 23. A waveguide as claimed in Claim 22, wherein the
6 thickness of the waveguide core is $6\mu\text{m}$.

7
8 24. A waveguide as claimed in any preceding claim,
9 wherein the lower cladding layer and the upper cladding
10 layer refractive indices are substantially equal.

11
12 25. A waveguide as claimed in any preceding claim,
13 wherein the lower cladding layer and the upper cladding
14 layer comprise the same material.

15
16 26. A waveguide as claimed in any preceding claim,
17 wherein the waveguide core has a mobile ion dopant
18 concentration higher than the mobile ion dopant
19 concentration of the lower cladding layer or the upper
20 cladding layer.

21
22 27. A waveguide as claimed in any preceding claim,
23 wherein the ion diffusion region is isotropic with
24 respect to the waveguide core.

25
26 28. A waveguide as claimed in any preceding claim,
27 wherein the ion diffusion region surrounding the
28 waveguide core forms a substantially rounded waveguide
29 core.

30
31 29. A waveguide as claimed in Claim 26 wherein the
32 rounded waveguide core is elliptical or circular in
33 cross-section.

34
35
36

1 30. A method of fabricating a waveguide comprising the
2 steps of:

3 providing a substrate;
4 forming a doped lower cladding layer;
5 forming a doped core layer on the lower cladding
6 layer;
7 forming a waveguide core from the core layer;
8 forming a doped upper cladding layer to embed the
9 waveguide core;

10 wherein mobile ion dopants included in the core
11 layer undergo diffusion into the surrounding upper
12 cladding layer and lower cladding layer to form an ion
13 diffusion region around the waveguide core such that
14 the waveguide core boundary walls are substantially
15 smooth.

16
17 31. A method as claimed in Claim 30, and including the
18 step of forming a buffer layer on the substrate.

19
20 32. A method as claimed in Claim 31, wherein the lower
21 cladding layer is formed on said buffer layer.

22
23 33. A method as claimed in any of Claims 30 to 32,
24 wherein the steps of forming each of the lower cladding
25 layer, the core layer and the upper cladding layer
26 comprise the steps of:

27 depositing each layer; and
28 at least partially consolidating each layer.

29
30 34. A method as claimed in Claim 33, wherein any of
31 the lower cladding layer, the core layer and the upper
32 cladding layer partially consolidated after deposition
33 is fully consolidated with the full consolidation of
34 any other of the lower cladding layer, the core layer
35 or the upper cladding layer.

36

- 1 35. A method as claimed in any of Claims 30 to 34,
2 wherein the diffusion of mobile ion dopants in the core
3 layer occurs during the consolidation of the lower
4 cladding layer and/or the upper cladding layer.
5
- 6 36. A method as claimed in any of Claims 30 to 35
7 further comprising at least one thermal processing step
8 after the formation of the upper cladding layer,
9 wherein during said thermal processing of the waveguide
10 the mobile ion dopants in the core layer undergo
11 diffusion into the surrounding layers.
12
- 13 37. A method as claimed in any of Claims 30 to 36,
14 wherein the substrate comprises silicon and/or silica
15 and/or sapphire.
16
- 17 38. A method as claimed in any of Claims 30 to 37,
18 wherein the buffer layer includes a thermally oxidised
19 layer of the substrate.
20
- 21 39. A method as claimed in any of Claims 30 to 38,
22 wherein the buffer layer comprises doped silica.
23
- 24 40. A method as claimed in any of Claims 30 to 39,
25 wherein the thickness of the buffer layer formed is in
26 the range of 0.2 μ m to 20 μ m.
27
- 28 41. A method as claimed in any preceding claim,
29 wherein the lower cladding layer comprises doped
30 silica.
31
- 32 42. A method as claimed in any preceding claim,
33 wherein the lower cladding layer includes at least one
34 Phosphorus oxide and/or Boron oxide.
35
- 36 43. A method as claimed in Claim 42, wherein the lower

1 cladding layer includes at least one Phosphorus oxide
2 and at least one Boron oxide and wherein the Phosphorus
3 oxide to Boron oxide ratio is such that the lower
4 cladding layer refractive index is substantially equal
5 to the refractive index of the buffer layer.

6
7 44. A method as claimed in any of Claims 30 to 43,
8 wherein the lower cladding layer includes silica, at
9 least one Phosphorus oxide and at least one Boron oxide
10 and wherein the silica; to Phosphorus oxide; to Boron
11 oxide ratio in the range of 75 to 95 wt% silica; to 1
12 to 7 wt% Phosphorus oxide; to 4 to 18 wt% Boron oxide.

13
14 45. A method as claimed in Claim 44, wherein the lower
15 cladding layer has a silica; to Phosphorus oxide; to
16 Boron oxide ratio in the range of 80 to 90 wt% silica;
17 to 2.5 to 6 wt% Phosphorus oxide; to 7.5 to 14 wt%
18 Boron oxide.

19
20 46. A method as claimed in Claim 45, wherein the lower
21 cladding layer has a silica; to Phosphorus oxide; to
22 Boron oxide ratio of 82 wt% silica; to 5 wt% Phosphorus
23 oxide; to 13 wt% Boron oxide.

24
25 47. A method as claimed in any of Claims 30 to 46,
26 wherein the thickness of the lower cladding layer is
27 $1\mu\text{m}$ to $20\mu\text{m}$.

28
29 48. A method as claimed in any of Claims 30 to 47,
30 wherein the core layer comprises doped silica.

31
32 49. A method as claimed in any of Claims 30 to 48,
33 wherein said mobile dopant ions of the waveguide core
34 include Phosphorus and/or Fluorine and/or compounds of
35 these elements.

36

- 1 50. A method as claimed in any of Claims 30 to 49,
2 wherein dopant ions of the waveguide core include
3 Phosphorus and/or Fluorine and/or Aluminium and/or
4 Boron and/or Germanium and/or Tin and/or Titanium
5 and/or compounds of these elements.
6
- 7 51. A method as claimed in any of Claims 30 to 50,
8 wherein the core layer includes Phosphorus oxide and/or
9 Boron oxide.
10
- 11 52. A method as claimed in Claim 51, wherein the core
12 layer comprises P_2O_5 - SiO_2 .
13
- 14 53. A method as claimed in any of Claims 30 to 52,
15 wherein the refractive index of the waveguide core
16 differs from that of the lower cladding layer by at
17 least 0.05%.
18
- 19 54. A method as claimed in any of Claims 30 to 53,
20 wherein the waveguide core includes silica and at least
21 one Phosphorus oxide and wherein the silica to
22 Phosphorus oxide ratio is in the range of 75 to 95 wt%
23 silica to 5 to 25 wt% Phosphorus oxide.
24
- 25 55. A method as claimed in Claim 54, wherein the
26 waveguide core has a silica to Phosphorus oxide ratio
27 of 80 wt% silica to 20 wt% Phosphorus oxide.
28
- 29 56. A method as claimed in any of Claims 30 to 55,
30 wherein the thickness of the waveguide core is in the
31 range $2\mu m$ to $60\mu m$.
32
- 33 57. A method as claimed in Claim 56, wherein the
34 thickness of the waveguide core is $6\mu m$.
35
- 36 58. A method as claimed in any of claims 31 to 57,

1 wherein said lower cladding layer and said buffer layer
2 are formed substantially in the same step.

3

4 59. A method as claimed in any of claims 33 to 58,
5 wherein the consolidation of the lower cladding layer
6 is at a temperature or temperatures in the range 950°C
7 to 1400°C.

8

9 60. A method as claimed in Claim 59, wherein the
10 consolidation of the lower cladding layer is at a
11 temperature or temperatures in the range 1100°C to
12 1350°C.

13

14 61. A method as claimed in any of Claims 33 to 60,
15 wherein the consolidation of the core layer is at a
16 temperature or temperatures in the range 950°C to
17 1400°C.

18

19 62. A method as claimed in Claim 61, wherein the
20 consolidation of the core layer is at a temperature or
21 temperatures in the range 1100°C to 1385°C.

22

23 63. A method as claimed in any of Claims 33 to 62,
24 wherein the consolidation of the upper cladding layer
25 is at a temperature or temperatures in the range 950°C
26 to 1400°C.

27

28 64. A method as claimed in Claim 63, wherein the
29 consolidation of the upper cladding layer is at a
30 temperature or temperatures in the range 1100°C to
31 1350°C.

32

33 65. A method as claimed in any of Claims 33 to 64,
34 wherein the temperature or temperature range at which
35 the lower cladding layer is consolidated is greater
36 than the temperature or temperature range at which the

1 core is consolidated.
2

3 66. A method as claimed in any of Claims 33 to 65,
4 wherein the temperature or temperature range at which
5 the upper cladding layer is consolidated is
6 substantially equal to the temperature or temperature
7 range at which the core layer is consolidated.
8

9 67. A method as claimed in any of Claims 33 to 67,
10 wherein at least one of the lower cladding layer, the
11 core layer, and the upper cladding layer is deposited
12 by a Flame Hydrolysis Deposition process and/or
13 Chemical Vapour Deposition process.
14

15 68. A method as claimed in Claim 67, wherein the
16 Chemical Vapour Deposition process is a Low Pressure
17 Chemical Vapour Deposition process or a Plasma Enhanced
18 Chemical Vapour Deposition process.
19

20 69. A method as claimed in any of Claims 33 to 68,
21 wherein the consolidation is by fusing using a Flame
22 Hydrolysis Deposition burner.
23

24 70. A method as claimed in any of Claims 33 to 68,
25 wherein the consolidation is by fusing in a furnace.
26

27 71. A method as claimed in either of Claims 69 or 70,
28 wherein the step of fusing the lower cladding layer and
29 the step of fusing the core layer are performed
30 simultaneously.
31

32 72. A method as claimed in any of Claims 30 to 71,
33 wherein the waveguide core formed from the core layer
34 is square or rectangular in cross-section.
35

36 73. A method as claimed in any of Claims 30 to 72,

1 wherein the waveguide core is formed from the core
2 layer using a dry etching technique and/or a
3 photolithographic technique and/or a mechanical sawing
4 process.

5
6 74. A method as claimed in Claim 73, wherein the dry
7 etching technique comprises a reactive ion etching
8 process and/or a plasma etching process and/or an ion
9 milling process.

10
11 75. A method as claimed in any of Claims 30 to 74,
12 wherein the diffusion of the said mobile dopant ions
13 from the waveguide core is isotropic.

14
15 76. A method as claimed in any of Claims 30 to 75,
16 wherein the diffusion of the said mobile dopant ions
17 from the waveguide core swells the boundary walls of
18 the waveguide core.

19
20 77. A method as claimed in Claim 76, wherein the
21 diffusion of the said mobile dopant ions swells the
22 boundary walls of the waveguide core to form a
23 substantially rounded waveguide core.

24
25 78. A method as claimed in Claim 77, wherein the
26 rounded waveguide core is elliptical or circular in
27 cross-section.

28
29 79. A waveguide substantially as described herein and
30 with reference to Figs. 2A to 2E of the accompanying
31 drawings.

32
33 80. A method of fabricating a waveguide substantially
34 as described herein and with reference to Figs. 2A to
35 2E of the accompanying drawings.

36